On-chip THz photonics with semiconductor frequency combs

G. Scalari[1], U. Senica[2], V.Digiorgio[1], M. Schreiber[3], M. Raffa[1], P.Micheletti[1], S. Gloor[1],C. Jirauschek[3], M. Beck[1], J. Faist[1]

[1] Institute for Quantum Electronics, Department of Physics, ETH Zürich, Zürich, Switzerland
[2]Laboratory for Nanoscale Optics, Harvard University, Boston, MA, USA
[3]Technical University of Munich (TUM), 85748 Garching, Germany

On-chip coherent THz signal generation and control [1] [2], is extremely appealing in a variety of different implementations from fundamental research to applications such telecommunication and spectroscopy. In the last 10 years, THz quantum cascade laser (QCL) frequency combs [3] have seen a tremendous development, with demonstration of dual-comb spectroscopy[4], dissipative Kerr solitons[5], passive and active mode locking [6], [7], [8]. We will discuss the generation of coherent THz signals in the bandwidth 1 to 5 THz and their on-chip manipulation. We leverage the frequency agility quantum cascade lasers (QCLs) combined with the ultrabroadband nature of double metal planarized waveguides to demonstrate broadband frequency combs operation both in AM and FM regimes.

Our group recently demonstrated a new active FM modelocking mechanism called the quantum walk comb [10] in Mid-IR QCLs. We will discuss unpublished results of quantum walk combs in on-chip THz ring resonators and also at telecom frequencies in external cavity ring lasers.

We will as well report on the generation of coherent pulse trains with arbitrary repetition rate from a monolithic on-chip device [9]. It is a novel regime of active mode-locking, which allows for an arbitrary amount of detuning between the modulation frequency f_{mod} and the natural repetition rate $f_{rep,0}$. We investigated a planarized THz QCL sample with $f_{rep,0}$ = 6.61 GHz by performing a modulation frequency sweep between 4-16 GHz . In this whole range we could observe AM mode locking with pulse generation for arbitrarily injected RF frequencies[9]. The experimental SWIFT spectroscopy at several widely detuned repetition rates yield a very good degree of coherence. We also developed a numerical simulation model based on a semiclassical Maxwell-density matrix formalism, whose results show excellent agreement with experimental data.

Wavelength division multiplexers (WDM) are essential components in signal processing. We will discuss as well the performance of an active, on-chip, three channels wavelength division multiplexer (WDM)[11]. Previously, on-chip THz WDM's were demonstrated at maximum frequencies below 500 GHz. A unique property of our WDM, conceived using inverse design, is that it is an active device with gain, allowing for simultaneous spectral selection and amplification. In Fig.1e is visible a micrograph of the processed device. Figures 1e and 1f display the amplification and the spectral output intensity for each channel. Experimental data show a good agreement with simulation. The integrated laser operates as a frequency comb, yielding an on-chip integrated device that produces coherent THz radiation and routes it in the bandwidth 2.6-3.2 THz.

References

[1] K. Sengupta, T. Nagatsuma, and D. M. Mittleman, “Terahertz integrated electronic and hybrid electronic-photonic systems,” NATURE ELECTRONICS, vol. 1, no. 12, pp. 622–635, (2018),

[2] S. Rajabali and I.-C. Benea-Chelmus, “Present and future of terahertz integrated photonic devices,” APL Photonics, vol. 8, no. 8, p. 080901, (2023)

[3] D. Burghoff et al., “Terahertz laser frequency combs,” Nature Photonics, 8, 6, 462–467, (2014).

[4] Y. Yang, D. Burghoff, D. J. Hayton, J.-R. Gao, J. L. Reno, and Q. Hu, “Terahertz multiheterodyne spectroscopy using laser frequency combs,” Optica, vol. 3, no. 5, p. 499, (2016)

[5] P. Micheletti et al., “Terahertz optical solitons from dispersion-compensated antenna-coupled planarized ring quantum cascade lasers,” Science Advances, vol. 9, no. 24, (2023)

[6] F. Wang et al., “Short Terahertz Pulse Generation from a Dispersion Compensated Modelocked Semiconductor Laser” Laser & Photonics Reviews, 11, 4,. 1770042 (2017)

[7] S. Barbieri et al., “Coherent sampling of active mode-locked terahertz quantum cascade lasers and frequency synthesis,” Nature Photonics, vol. 5, no. 5, pp. 306–313,(2011)

[8]U. Senica et al., “Planarized THz quantum cascade lasers for broadband coherent photonics,” Light: Science and Applications, vol. 11, no. 347, 2023.

[9] U. Senica et al., “Continuously tunable coherent pulse generation in semiconductor lasers.” 2024. [Online]. Available: https://arxiv.org/abs/2411.11210

[10] I. Heckelmann, M. Bertrand, A. Dikopoltsev, M. Beck, G. Scalari, J. Faist, “Quantum walk comb in a fast gain laser ”, Science 382 (6669), 434-438

[11] V. Digiorgio, U. Senica, P. Micheletti, M. Beck, J. Faist, and G. Scalari, “On-chip, inverse-designed active wavelength division multiplexer at THz frequencies,” Nature Communications, vol. 16, no. 1, p. 7711, (2025)